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Kinetic Inductance Detectors for X-Ray Spectroscopy

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Abstract

The lack of efficient x-ray detectors is often the main factor limiting the effective use of ever more powerful synchrotron light sources. Spectroscopic X-ray detectors are used for a wide variety of synchrotron experiments including X-ray micro/nano-probes and X-ray absorption spectroscopy for biology and geophysical applications. The current state-of-art spectroscopic X-ray detectors are semiconductor devices, and their energy resolutions are approaching their theoretical limit of about 100eV at 6 keV. We describe a detector research and development program to develop the next-generation of high-resolution spectroscopic X-ray detectors using superconducting Kinetic Inductance Detectors (KIDs). With a required energy per charge carrier four orders of magnitude smaller than that of Si, superconducting detectors offer up to two orders of magnitude increase in energy resolution. In addition, KIDs can be optimized for detection of photons ranging in energy from hard X-ray to IR.

Keywords: kinetic inductance detector; x-ray spectroscopy;

1. Introduction

Considerable time and financial resources have been spent in recent years on improving the capabilities of synchrotron light sources. These upgrades have focused on increasing source brightness and energy, and improved temporal resolution. A comparatively cost effect method for improving overall facility capabilities is to invest in the improvement of x-ray detectors. Detectors can roughly be divided

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into two categories: diffraction and spectroscopic. Spectroscopic detectors are used for a wide range of applications including: scanning x-ray fluorescence (XRF) micro/nano-probes[1], 3D elemental microtomography[2], and X-ray absorption spectroscopy (XAS)[3]. We have chosen to focus on energy dispersive detectors where the state-of-the-art silicon drift diode detectors are reaching their theoretical energy resolution limits. These detectors are limited by uncertainty in statistical fluctuation of the charge carriers produced by incoming photons, or Fano noise. To increase the energy resolution of the detector for a given photon energy, the number of charge carriers needs to be increased. This can be achieved by reducing the energy gap of the material. Superconductors have energy gaps that are two to three orders of magnitude lower than silicon and can offer improvement in energy resolution by a factor of 10 to 100. Superconducting detectors have been investigated for use at synchrotrons for many years and are in place at several[4,5]. One challenge that has limited many of these detectors is the ability to cover a large solid angle and limited count rate performance. We have started a program to look into superconducting kinetic inductance detectors that offer increased energy resolution and an inherent path to multiplexing large arrays for improved count rates and solid angle.

2. Superconducting Kinetic Inductance Detector

Currents in a superconductor can be described using a two-fluid model[6]: a current of electron pairs (copper pairs) and a current of single electrons (quasi-particles). In the presence of a static electric field, the pair current flows with no resistance, shorting out the single electron current. In the presence of an alternating field, the superconductor has non-zero impedance. The electron pairs are accelerated with the field storing kinetic energy, which can be extracted by reversing the field due to the lack of dissipation. Energy can also be stored in the magnetic field, which penetrates in to the superconductor to a length λ. The reactive flow of energy between the superconductor and the electromagnetic field results in a kinetic inductance $L_s = \mu\lambda$, which contributes to the total surface impedance, $Z_s = R_s + j\omega L_s$, where Rs is the surface resistance. For temperatures much less that the critical temperature, $R_s << L_s$. The surface impedance changes with the ratio of the number densities of the pair and single electrons. When a photon with energy greater than the gap energy strikes the superconductor, electron pairs are broken generating single electrons according to $N_{qp} = \eta h\nu/\Delta$. Thus the energy deposited in the superconductor results in an increase in single electrons and kinetic inductance and a change in surface impedance.

Although the change in surface impedance with quasi-particle density is small, approximately $\delta Z_s/Z_s = \delta N_{qp}/2N_0\Delta$, where N_0 is the single spin density of states at the Fermi energy of the metal, it can be read out by forming the superconductor into a high quality resonator[7]. When operated at well below the critical temperature, the lossless nature of the superconductor enables the creation of resonators with quality factors in excess of 1 million[8, 9,10]. The change in kinetic inductance is scaled by the quality factor. The resonant frequency is determined by the inductance and capacitance of the resonator, $f_0 \approx \sqrt{}(LC)$, where L consists of both the geometric and kinetic inductance. When a photon with energy greater than the gap energy strikes the superconductor, electron pairs are broken generating quasi-particles according to $N_{qp} = \eta h\nu/\Delta$, The increase in quasi-particles raises L_s and R_s, lowering the resonant frequency and broadening the resonance. The energy deposited into the resonator can be determined by monitoring the change in the magnitude or phase of a microwave tone sent past the resonator.

Using high quality factor resonators as detectors results in an inherent frequency domain multiplexing scheme. The resonator is readout by capacitive coupling to a transmission line as shown in the circuit diagram in Figure 1a. The transmission past the resonator dips as the frequency approaches the resonance frequency and is near unity for frequencies off resonance. A simulation of the transmission past the resonator before and after a photon hits in Figure 1b. By designing each resonator to operate at a different resonance frequency, arrays of resonators can be coupled to a single transmission line. In operation a frequency comb is generated consisting of the resonant frequency of each resonator in the array and sent along the transmission line, exciting each individual resonator. The number of resonators that can be multiplexed on a single transmission line depends on several factors including quality factor, lithographic precision, crosstalk, and amplifier bandwidth and power. At a minimum the spacing between resonators must be larger than the width of the resonance. With a quality factor of 10^5 and a resonance frequency of 5 GHz, the resonance width is 50kHz. For a lithographic error of $\delta L = 0.2\mu m$, a 5GHz resonator of length 6mm would have a frequency error of $f_0\delta L/L$ = 175kHz. Even with a spacing of 1MHz to help limit cross talk 1000 resonators could fit in a 1GHz bandwidth[8]. Much work is being done in the area of cryogenic amplifiers and amplifiers over 4 GHz bandwidth are becoming commercially available [11].

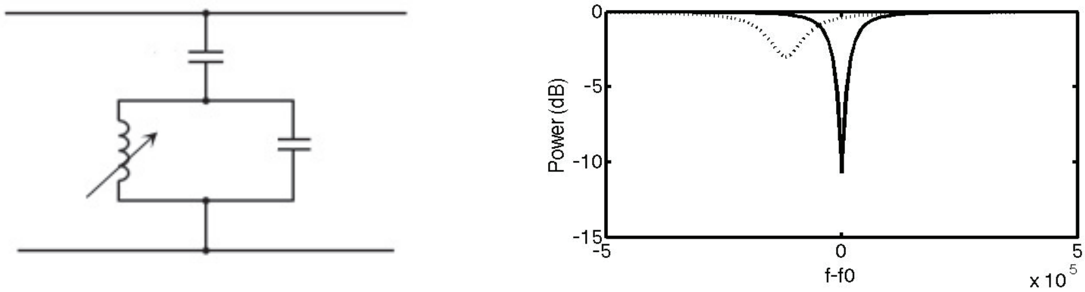

Fig. 1. (a) Circuit diagram of a resonator coupled to a transmission line; (b) Transmission past a resonator before (solid) and after (dotted) being hit by a photon with energy greater than 2Δ. The shift in depth and frequency of the resonance is determined by the photon energy.

3. Detector Design

There are two main designs for superconducting kinetic inductance detectors: the quarter wavelength transmission line resonator and the lumped element resonator. Depending upon experimental conditions such as photon energy, count rate, and fill factor, each has advantages and drawbacks.

A simple way of creating a resonator at microwave frequencies is to use a quarter wavelength transmission line resonator; the resonant frequency is easily adjusted by changing the length of the line. One end of the resonator is shorted to ground while the other end is capacitively coupled to the transmission line. The shorted and capacitively coupled ends of a set of co-planar waveguide resonators are shown in figures 2a and 2b, respectively. The current and voltage vary along the length of the line with the current highest (and voltage lowest) at the shorted end of the resonator, making this location the most sensitive part of the line. This can be taken advantage of to yield maximum sensitivity by coupling incoming radiation to the shorted end of the transmission line using antennas[11] for far inferred and optical photons and a separate absorbers for x-rays and gamma rays[8].

The resonator/absorber design offers the advantage of having different film thicknesses and/or materials for the resonator and absorber. The sensitivity of KIDs increases with decreasing film thickness (i.e., volume) and typical resonator thickness are on the order of 100nm. At this thickness the stopping power for x-rays and gamma rays is limited. The absorber, meanwhile, can be made much thicker without decreasing detector sensitivity. By making the absorber from a material with a larger energy gap than the resonator, quasi-particles that diffuse into the resonator will drop in energy to the gap of the resonator and then be unable to diffuse back into the absorber, where they can recombine without being detected. Additionally, this design can be used to create a position sensitive strip detector by placing resonators at each end of an absorber strip. By comparing the amplitude and arrival time of the signal in each of the detectors, the total energy deposited in the strip and the location can be determined.

The main drawback of this detector is the extra complexity from adding a second layer. A high quality interface between the resonator and absorber is needed to assure the free flow of quasi-particles. This has been achieved with Al resonators and Ta absorbers[12] but has not been widely developed. The choice of absorber can limit the dimension of the absorber, as a material with a large diffusion length is desired so that all the quasi-particles generated can make it into the resonator before recombining. This is especially important in strip detectors as it determines the length of the strip that can be used before seeing incomplete quasi-particle collection. However, a large diffusion length often indicates a large quasi-particle lifetime, which can limit the overall detector speed.

For detectors operating in the sub-mm to optical range, the stopping power is not as great an issue as coupling the incident radiation into the detector. Although this can be done using a separate antenna, Doyle et al.[13] proposed a means of using the detector as the antenna with lumped element KIDs (LEKID). The LEKID uses lumped elements, inter-digitated fingers for capacitance and a meander for inductance, rather than a transmission line for the resonator. A schematic of an LEKID is shown in Figure 2c. By adjusting the capacitance of the inter-digitated capacitors the resonant frequency can be tuned while leaving the overall detection area (meander size) unchanged. At resonance, current flows in the meander, making the entire meander the detector. By properly spacing the legs of the meander, the inductor can be matched to the skies impedance and thereby also serving as the antenna.

The main advantage of a LEKID is the simplified fabrication. Only a single material layer is need for the entire device, eliminating extra processing steps and interfaces. With careful engineering, the device can be design to yield a highly uniform current in the meander section to create a large active detector region. Also, because these detectors can easily be designed with a square form factor, they can yield a much higher packing density than quarter wave transmission lines.

A major challenge for LEKIDs for use with higher energy photons such as x-rays is stopping power. Thicker films are needed to stop higher energy photons, but this increases the volume of the detector and decreases the sensitivity. An additional challenge is the device design. Because the entire meander serves as the detector, any variation in current along the meander results in a position dependent sensitivity. This can be overcome with careful design, but has to be closely monitored. A potential application for LEKIDs in the x-ray range is a phonon detector. An array of LEKIDs is arranged on the surface of a wafer and the entire wafer acts as the absorber [14]. X-rays striking the wafer create phonons that travel to the LEKID and break electron pairs in the superconductor.

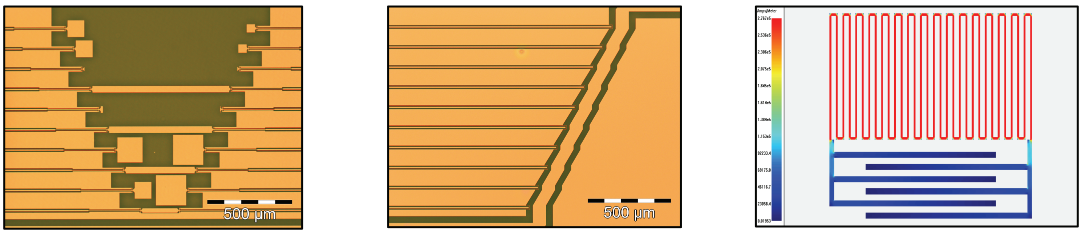

Fig. 2. (a) Optical photograph of shorted ends of quarter wave resonators. The resonators are connected to absorbers of various sizes with some pairs of resonators in the strip detector configuration; (b) Optical photograph of quarter wavelength resonators capacitvely coupled to a transmission line; (c) model of a LEKID used for electromagnetic simulations showing the meander inductor and inter-digitated capacitors. The colors represent magnitude of current density in the superconductor.

4. Kinetic Inductance Detectors at Argonne National Laboratory

We have started a new program at Argonne to develop KIDs for use with synchrotron x-ray spectroscopy. We began materials work with Al quarter wave CPW resonators. Al resonators have been used previously to achieve high quality factors[8], and with a T_C of about 1.15K have a theoretical energy resolution of ~2eV at 6keV. We have fabricated resonators with 300nm thick Al film deposited using dc magnetron sputtering. The resonators show an internal quality factor of over 10^6. The transmission past one resonator can be seen in Figure 3a along with a fit to the data using a skewed Lorentzian.

Tantalum has been proposed as a possible KID absorber for x-ray applications due to its high Z-number[12]. It has an attenuation length of 1.79μm at 6keV and with a T_C of 4.5K and a theoretical energy resolution of 2.79eV. The major challenge with Ta absorbers is controlling the phase of the deposited film. Ta can be deposited in either an alpha (bcc) or beta (fcc) phase[15]. The beta phase is not superconducting, while the alpha phase has a T_C of 4.5K and long diffusion lengths. To achieve the best diffusion lengths epitaxial alpha phase tantalum is desired. This can be achieved by depositing Ta on R-plane sapphire at 800C. A relative measure of the diffusion length can be achieved by measuring the residual resistance ratio (the ratio of resistance at 300K to 5K)[16]. We have deposited epitaxial Ta films with a residual resistance ratio of over 30 for 300nm films, indicating a high quality film.

A possible alternative to Ta films is WSi_x alloys, which can have similar T_C and attenuation lengths. These materials can be deposited at room temperature on a range of substrates. The critical temperature and resistivity vary with W content enabling tuning of the device properties for the specific application [17]. We have been examining WSi_2 and W_5Si_3 stoichiometry. Initial results indicate that we can achieve high quality factors of greater than 10^5. The transmission past one resonator can be seen in Figure 3b along with a fit to the data using a skewed Lorentzian. Additionally, these materials show a large kinetic inductance fraction (ratio of kinetic inductance to geometric inductance), which allows for more sensitive resonators and can been seen in the shift to lower frequencies – here 4.6GHz instead of the design frequencies of 6.2GHz. These materials may also be of interest for KID applications in the sub-mm to optical range due to their high normal state resistivity, which allows for efficient Far IR absorption[13].

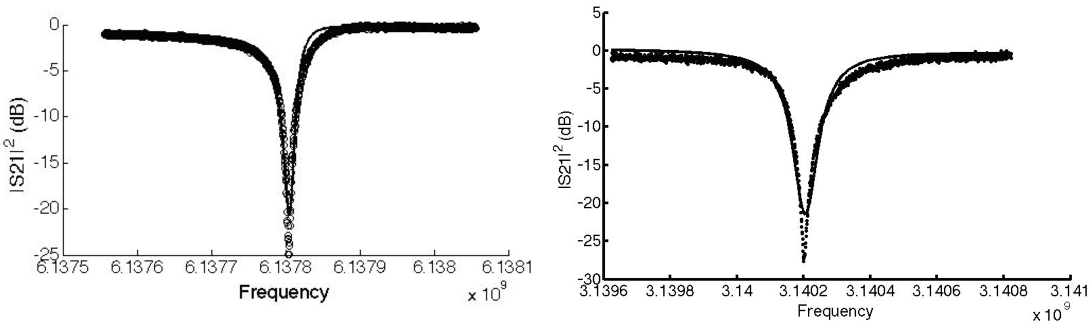

Figure 3. (a) Resonance from a 300nm thick Al resonator at 100mK with internal quality factor of $2.38\ x\ 10^6$. (b) Resonance from a 300nm thick W_5Si_3 resonator at 100mK with internal quality factor of $2.56\ x\ 10^5$.

5. Conclusions and Future Work

We have started a research and development program at Argonne for the next generation of spectroscopic x-ray detectors based upon superconducting kinetic inductance detectors. We have procured the necessary infrastructure (adiabatic demagnetization fridge, microwave electronics, deposition systems) and have begun to fabricate single layer resonator structures with high quality factors: 10^6 for Al resonators and 10^5 for WSi_x alloys. We are investigating alternate materials for x-ray applications and studying alternate detector designs such as the LEKID. We have begun designs of LEKIDs for x-ray applications using the SONNET EM software. Finally, we will soon begin work with a ROACH board readout scheme. The ROACH board [18] is an open source electronic system developed by the CASPER collaboration. It combines an FPGA board with high speed ADC and DAC to create the input frequency comb sent to the resonator array and analyze system response.

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